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# Quantitative Study of Laser Cooling in a Penning Trap*

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Penning traps are currently being studied at our laboratory [1,2] and elsewhere [3,4] for use in atomic frequency standards. A Penning trap confines ions by a combination of a static, uniform magnetic field and a static, nonuniform electric field. The fact that the fields are static makes it feasible to laser cool more than $10^4$ ions to low temperatures [5]. In contrast, the radio-frequency (Paul) ion trap uses oscillating electric fields, which, in combination with the non-linear Coulomb coupling between ions, cause heating and make it difficult to laser cool large numbers of ions [6]. For either trap, large numbers increase the signal-to-noise ratio; low temperatures reduce the second-order Doppler shift [7].

Several experimental groups have reported laser cooling of ions confined in Penning traps to temperatures below 1 K [1-5,8-10]. Typically, the measured temperatures were one or two orders of magnitude higher than the theoretical limit $T_{min} = \hbar\gamma_0/(2k_B)$ (about 1 mK), where $\gamma_0$ is the natural linewidth of the optical transition used for laser cooling [9]. The reason for this discrepancy is now understood [10]. The rotation of the ion plasma about the magnetic field axis, due to the presence of crossed electric and magnetic fields, has a great effect on the temperature. In order for the ion plasma to be stable, it is necessary to displace the laser beam radially so that it illuminates the side of the plasma which is receding from the laser. The radiation pressure applies a torque to the plasma which counteracts the torques induced by axially nonsymmetric, static electric and magnetic fields. This radial displacement of the beam, however, results in higher temperatures. The reason stems from the requirement that the work done by the laser on the ions be zero for a steady state. The rate at which work is done on an ion of velocity $\vec{v}$ by a force $\vec{F}$, which, in this case, is parallel to the direction of propagation of the laser beam, is $\vec{F}\cdot\vec{v}$. Because of the radial displacement of the beam and the plasma rotation, $\vec{F}\cdot\vec{v}$ tends to be positive. In order to make the average value $\langle\vec{F}\cdot\vec{v}\rangle$ be zero, the frequency of the laser must be tuned below the optical resonance. Because of the Doppler shift, this makes $\vec{F}$ stronger for ions with $\vec{F}\cdot\vec{v} < 0$ than for ions with $\vec{F}\cdot\vec{v} > 0$. The width of the velocity distribution must have a particular value in order for cancellation between negative and positive contributions to make the average value be zero. The required width increases with the rotation frequency and with the distance of the laser beam from the axis of rotation of the plasma. This width corresponds to a temperature higher than $T_{min}$.

Temperatures and rotation frequencies of $^9Be^+$ plasmas were measured for a wide range of experimental parameters [10]. The measured temperatures varied from 40 mK to 2 K. These measured temperatures were in agreement with the calculation, within an rms error of about 10%. For these measurements, the cooling laser beam was in the plane perpendicular to the magnetic field. Lower temperatures have been attained by the use of laser beams whose direction of propagation were not perpendicular to the magnetic field axis, but the calculation in this case is more complicated [5].

For certain ranges of laser frequency detuning and beam position, we have observed strong oscillations in the total ion fluorescence, with periods from less than a second to over a minute. These oscillations have been observed in all Penning traps at our laboratory and are similar to those reported by others [3,11]. Sometimes, a deliberate misalignment of the magnetic field direction with respect to the trap axis was necessary in order for oscillations to occur. This was an indication that external torques were involved. An ion plasma undergoing oscillations was observed with a photon-counting imaging tube. The change in ion fluorescence was accompanied by a change in the radius (which is directly related to the total canonical angular momentum) of the plasma. For the plasma to reach a steady state, the rate of both the energy and angular momentum imparted to the plasma by external forces must be 0. Apparently, these two conditions sometimes cannot be satisfied simultaneously, and this leads to oscillations.

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